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DIAMAGNETICALLY LEVITATED MEMS ACCELEROMETERS

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Abstract: We introduce the theory and a proof-of-concept design for MEMS-based, diamagnetically-levitated accelerometers. The theory includes an equation for determining the diamagnetic force above a checkerboard configuration of magnets. We demonstrate both electronic probing and a rapid MEMS-based interferometer technique for position sensing of the proof mass. Through a proof-of-concept design, we show electrostatic-measurement sensitivity achieving 34 µg at a 0.1 V sense signal and interferometer-measurement sensitivity achieving 6 µg for in-plane vibrations at 5 Hz. We conclude by outlining batch-fabrication steps to produce levitated accelerometers.

Keywords: accelerometer, diamagnetism, levitation, fast phase-shifting interferometer

1. INTRODUCTION

This research presents the theory and verification for a MEMS-based, diamagnetically levitated proof mass to improve the low-frequency performance of accelerometers for applications such as the study of earthquakes and structural health monitoring. We have built a levitated proof-mass device and obtained experimental results that show electrostatic-measurement sensitivity of 34 µg at a 0.1 V sense signal and interferometer-measurement sensitivity of 6 µg. The measurements are targeting 5 Hz vibrations. An ADXL 203, a commercial MEMS accelerometer, achieves 285 µg for the same vibrations. Previous approaches to levitating a proof mass in a MEMS process use electrostatic active control and suffer from stiction [1]. In our accelerometer, diamagnetism is employed to passively levitate a proof mass containing pyrolytic graphite [2]. We measure the position of the proof mass using off-chip circuitry that differentially senses the change in capacitance across a pair of comb drives. The comb drives are fabricated in an SOI process [3].

2. EQUATIONS OF MOTION

We show that a lightly damped, non-stiff suspension gives more precise results when measuring low-frequency vibrations than does the stiff suspensions that are typically used in MEMS accelerometers. Diamagnetic levitation provides the means to create these optimized suspensions.

The 1D mechanical theory for accelerator response is formulated in Eq. 1. Calling x the target displacement, the acceleration $\ddot{x}(t)$ is:

$$\ddot{x}(t) = -\frac{1}{M}\left(D\dot{z}(t) + Kz(t)\right) - \ddot{z}(t), \qquad (1)$$

where $y(t)$ is the proof-mass position, $z(t) = y(t)-x(t)$ is the measured displacement, and M, D, and K are the mass, damping, and stiffness of the system. We simulate the response of this system to a 10 µg sinusoidal excitation over a frequency range from 0.1 to 10 Hz (Fig. 1). The assumed noise of the position detector has a standard deviation of 1 nm when sampling at 500 Hz.

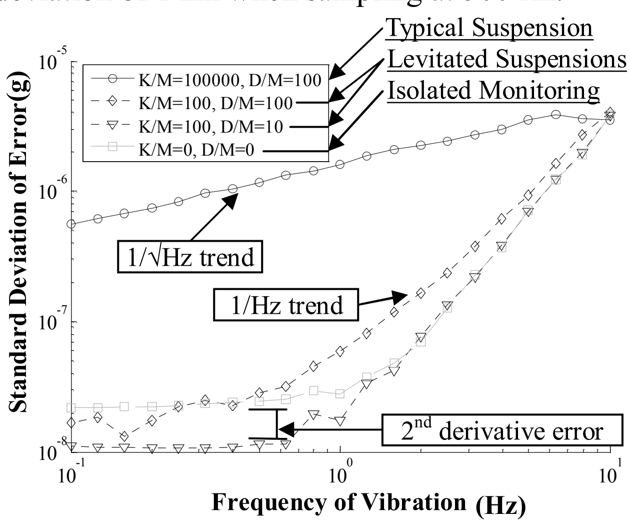

Figure 1: The accuracy of accelerometers using four different suspensions is measured by finding the standard deviation of the suspension response compared to a sinusoidal input at each frequency.

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3. DIAMAGNETIC FORCE

Using Fourier analysis and Taylor-series expansions applied to the diamagnetic governing equations [2] of a square plate of graphite above a checkerboard configuration of magnets (Fig. 2), we derive Eq. 2 which approximates the plate-levitation height z when the proof-mass weight balances the diamagnetic force (Fig. 3):

$$h_{total}\rho g A + F_{load} \approx 0.235\frac{16\chi}{\pi^5\mu_0}B^2\left(\frac{h_{graphite}w}{(z+h_{graphite})z}\right)A, \quad (2)$$

where h_{total} is the total plate thickness, ρ is the plate density (2300 kg/m^3), g is 9.8 m/s^2, A is the plate area (8mm × 8mm), F_{load} is the vertical load applied to the plate, χ is graphite's magnetic susceptibility (450×10^{-6}), μ_0 is $4\pi\times10^{-7}$ N·A^{-2}, B is the magnetic flux density (1 Tesla for NdFeB), $w \times w$ is the magnet size (100 µm × 100 µm), and $h_{graphite}$ is the graphite-layer thickness.

We verify Eq. 2 by placing weights onto a levitated plate of pyrolytic graphite (7.7×10^{-5} N) while monitoring the vertical displacement through a side-mounted microscope (Fig. 3a). We reduce tilting of the proof mass by positioning the weight while monitoring the angular change of a reflected laser beam. We also compare adding additional pieces of pyrolytic graphite (Fig. 3b).

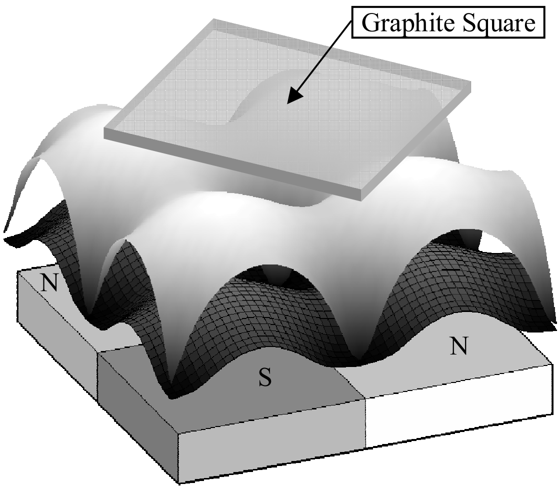

Figure 2: Two equipotential surfaces of the diamagnetic field above alternating north- and south-pole magnets (potential increases closer to the magnets).

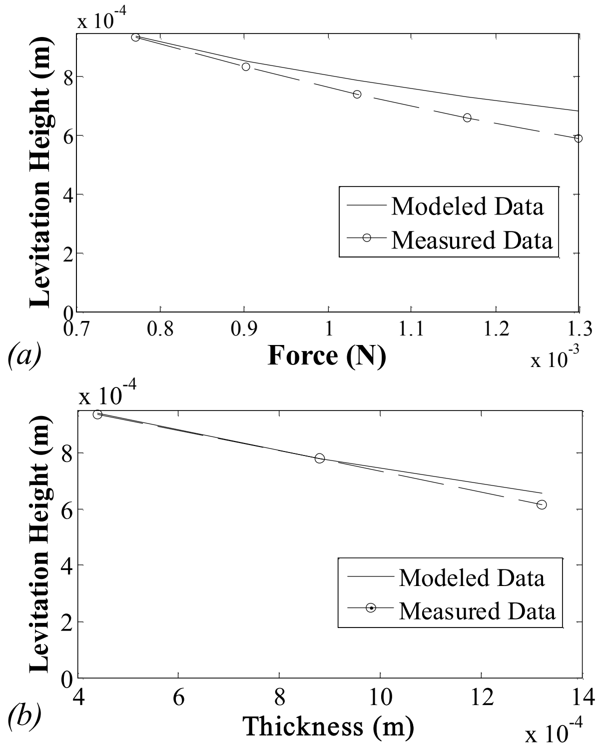

Figure 3: Theoretical (Eq. 2) and experimental measurements of the levitation height of the proof mass (a) under varying load and (b) with varying thicknesses of graphite.

4. PROOF-OF-CONCEPT RESULTS

To test the MEMS levitated accelerometer, we mount a fabricated SOI proof mass to several layers of pyrolytic graphite. We levitate it above NdFeB magnets and align the electrostatic-sensing combs to it using a 3-axis stage (see Fig. 4a). We measure and compare the responses of our levitated accelerometer to those of the ADXL 203 accelerometer when both are subjected to tapping impulses applied to the support table (see Fig. 4). We reflect a laser beam off of the proof mass and record its position on a CCD image sensor to measure out-of-plane tilting motions of the plate (Fig. 6). By processing the results using off-chip circuitry, we show that the noise level of the levitated accelerometer is at least a factor of 8.4 smaller than the noise level of the ADXL 203 using only 0.1V for the differential sense (specific results are at 5 Hz). Upon excitation of the air table, a higher-frequency (40 Hz) tilting-mode coupling is measured. We can reduce the amplitude of this mode by packing more magnets under the levitated proof mass.

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At rest, the standard deviations of the ADXL and our levitated accelerometer measure, respectively, 285 µg and 34 µg when we use a 0.1 V sense signal and average signals over 0.1 seconds. A larger sense voltage increases the sensitivity of the detector (0.34 µg possible at a 10V applied signal). Note that added aluminum, produces the desired damping of in-plane motion.

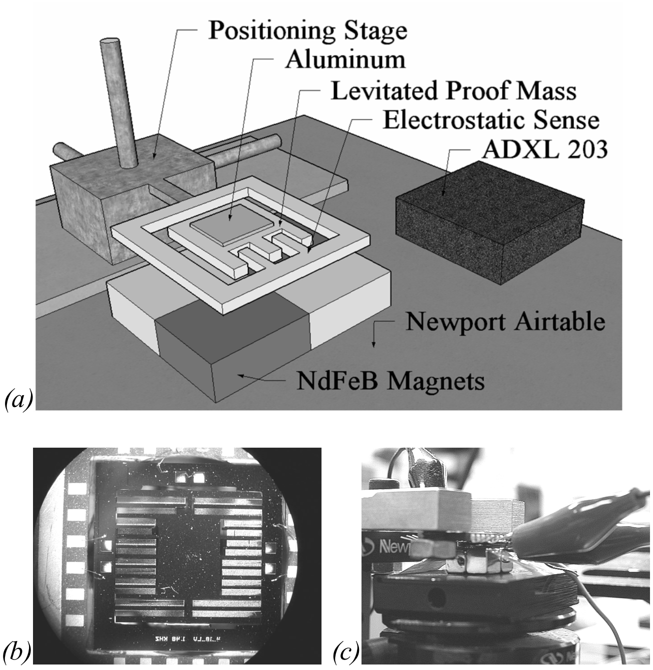

Figure 4: (a) Schematic of experimental setup; (b) microscope photo of levitated proof mass; (c) the magnets under the levitated proof mass.

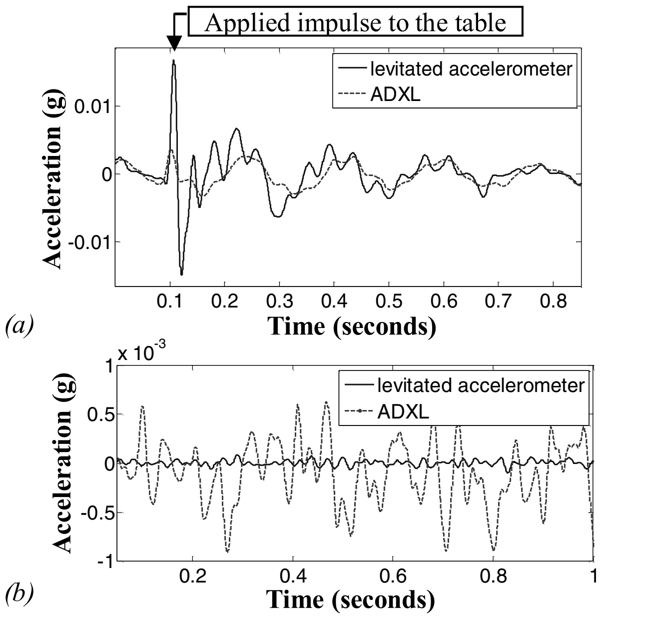

Figure 5: Comparison of an ADXL 203 and the levitated accelerometer excited (a) and at rest (b).

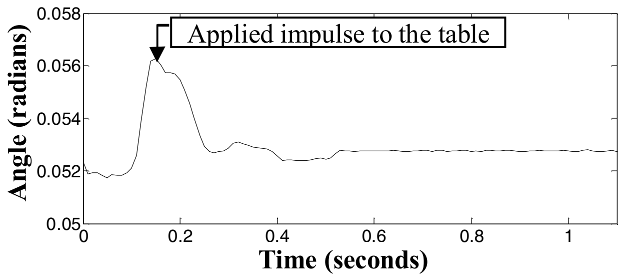

Figure 6: Tiling of the levitated proof mass occurs in the first 0.4 seconds and then stabilizes.

Next, we examine the motion of a diamagnetic proof-mass (D/M = 73 Hz, K/M = 4 Hz^2) with a fast phase-shifting interferometer. This interferometer uses a vibrating MEMS plate to achieve rapid phase-shifting and therefore a high sampling rate (50 Hz) [5] (Fig. 7). We use a Fisher Scientific U56001 vibration generator to supply a 1.6 N impulse to the 300 Kg Newport air table. From the response measured by the levitated accelerometer (Fig. 7), we are able to determine the table's suspension values, K/M ≈ 11.1 Hz^2 and D/M ≈ 2.3 Hz. The noise in the system has a standard deviation of 6.0µg, not the limit of the detector but the limit of isolating the table from surrounding vibrations.

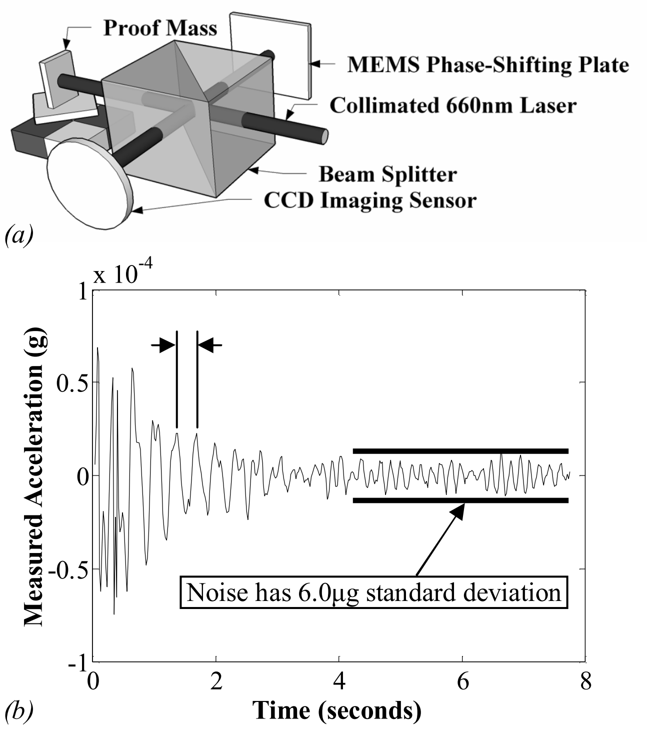

Figure 7: The fast phase-shifted interferometer (a) measures the acceleration (b) of the 300 kg air table after a 1.6 N impulse is applied to it.

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5. IDEAL FABRICATION AND DESIGN

We show the feasibility of a MEMS process to fabricate a levitated accelerometer with the necessary levitation height and dynamic properties. Evaluating Eq. 2, we calculate a levitation height of 26 μm for a 2 μm-thick pyrolytic graphite layer [4] on top of a 20 μm-thick silicon plate with square magnets (100 μm on a side) fabricated on the substrate. The magnet arrays can be made separately and bonded to the device to reduce complexity. Thus, the plate is separated by a 6 μm-gap from the substrate and magnets. Depositing a 0.122 μm layer of aluminum on top of the plate results in eddy current damping of $D/M = c\, B^2/\rho\ h_{aluminum}/h_{total} = 100$ Hz, where c is aluminum's conductivity (37.7×10^6 /ohm m).

Fig. 8 shows a conceptual view of a processed device. The magnets can be made separately and placed in a backside trench or opening. Additional magnets should be placed above to keep the proof mass in place during the release of the proof mass from its surrounding, and to lessen out-of-plane tilting effects during operation.

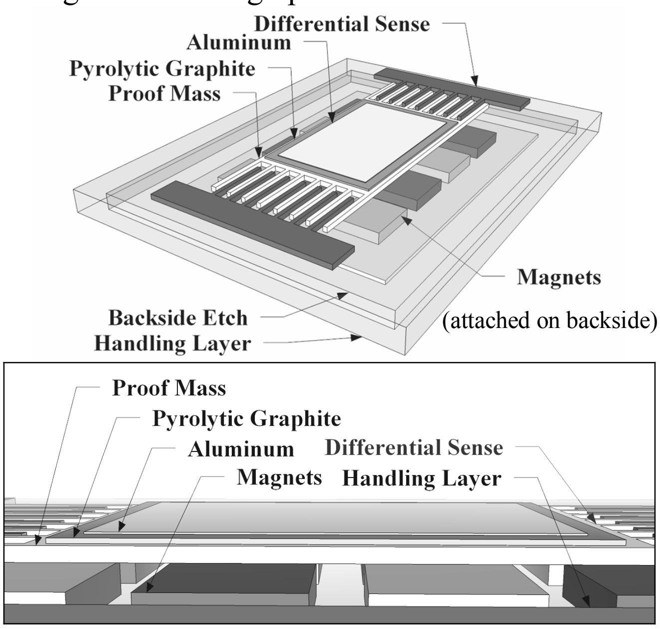

Figure 8: The levitated proof mass construction.

Differential comb-drives are used in electrostatic sensing for accurately determining position. Differential vertical-offset combs can be fabricated directly in SOI to electrostatically sense out-of-plane motion [3] (Fig. 9).

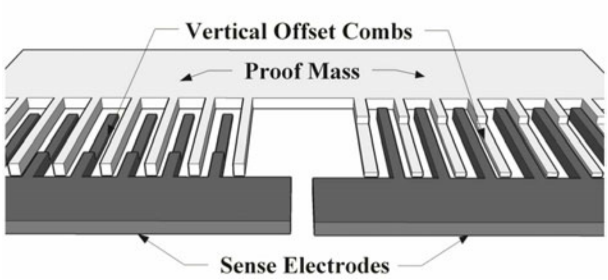

Figure 9: Vertical sensing using offset combs.

The levitated accelerometer can be designed to use either electrostatic sensing or interferometric sensing. As demonstrated, using fast phase-shifting interferometer techniques, we can inexpensively and rapidly monitor lateral motions at frequencies above 100 Hz with a precision better than 2 nm per frame.

6. CONCLUSIONS

We have shown that diamagnetically levitated accelerometers perform well at measuring low-frequency vibrations below 5 Hz. Using electrostatic measurements, we achieve 34 μg sensitivity at a 0.1 V sense signal. Using interferometer measurements, we achieve 6 μg sensitivity. Furthermore, we have shown that such accelerometers are possible in MEMS.

REFERENCES

[1] B. Damrongsak and M. Kraft. *Electrostatic suspension control for micromachined inertial sensors employing a levitated-disk proof mass.* Proc. MME 2005 Conference, Sept. 2005, pp. 240-243.

[2] M. V. Berry et al. *Of flying frogs and levitrons*. Eur. J. Phys. Vol. 18, 1997, pp. 307-313.

[3] H. Choo et al. *A simple process to fabricate self - aligned, high - performance torsional microscanners: demonstrated use in a two-dimensional scanner*. 2005 IEEE/LEOS Optical MEMS, August 1-4, 2005, pp. 21-22.

[4] Kostecki et al. *Surface studies of carbon films from pyrolized photoresist*. Thin Solid Films, 396, (2001).

[5] H. Choo et al. *Fast, MEMS-Based, Phase-Shifting Interferometer*. Solid-State Sensor and Actuator Workshop, June 4-8, 2006, pp.94-95, Hilton Head, SC USA.

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